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MEMORANDUM REPORT ARBRL-MR-02912

DESIGN OF A LOW L/D DEEP EARTH PENETRATOR

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US ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
BALLISTIC RESEARCH LABORATORY
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Steel cylindrical and tapered projectiles weighing 425 grams and having a L/D ratio of 5 were fired against concrete/clay targets at striking velocities of 305 and 610 m/s. It was found that low L/D projectiles with tapered bodies appear to be a feasible solution for systems requiring predictable deep earth penetrators. It appears that minimum body taper required for stability probably increases with increasing striking velocity. Path deviation seems to decrease with increasing striking velocity. Results of the tests indicate (over)

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20. Abstract (Cont)

that the delay of onset of rapid yaw and swerve growth is increased as striking yaw is decreased, which is especially true for projectiles with very small yaws. The tapered projectile concept offers promise as an earth penetrator for both tactical nuclear and conventional weapon systems.

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I. INTRODUCTION

The Defense Nuclear Agency (DNA) contracted with the Ballistic Research Laboratory (BRL) to design and test the stability, in earth, of low length to diameter (L/D) penetrators.

Designs for stable, deep earth penetrators exist but are of relatively long length, L/D of 10. Since such lengths are excessive under certain weapon system constraints, an exploratory program of short projectiles, L/D = 5, fired into concrete/clay targets was conducted for several bi-metal designs of substantially different contour. The objective was to zero in on a design class with good survivability through a concrete or rock layer and with sufficient stability during deep earth penetration to estimate the trajectory with a degree of confidence for optimum time of detonation. Specifically, the BRL was asked to select two projectile geometries and design monobloc penetrators and compare their stability when fired into a concrete/clay target. This report presents the results of this experiment.

II. PROJECTILE DESCRIPTION

Figure 1 shows schematics of the projectiles. The projectiles were fabricated from AISI-S7 tool steel and heat treated to a Rockwell C number of 55. These two designs, having shown better penetration and stability, were chosen from seven designs, Figure 2, tested for DNA by Physics International (PI)[1]. The original seven designs were radically different concepts proposed by personnel from DNA, BRL, US Army Waterways Experiment Station, and PI. The ogive cylinder was originally proposed as a baseline design. The tapered projectile with ogive nose was proposed by the BRL, the rationale being that continuously and sufficiently increasing the cross section toward the base might provide greater stability by additional contact (toward the rear) between earth and penetrator. This additional contact might occur by balloting (tail-slap) or by moving the formation of the cavity rearward. (Fins could also provide rear contact, but they may have greater survivability problems when penetrating a rock layer. Finned configurations were included in the seven original designs and they did break up.)

The ogival masses of the two designs are the same; hence, the base diameter of the tapered projectile is necessarily greater than the cylindrical, three-to-two. Since it was desired to maintain the same weight, 428 grams, and the same overall length, 12.7cm, it was necessary to bore cavities through the aft sections of the projectiles. Table I gives the physical properties of the projectiles.

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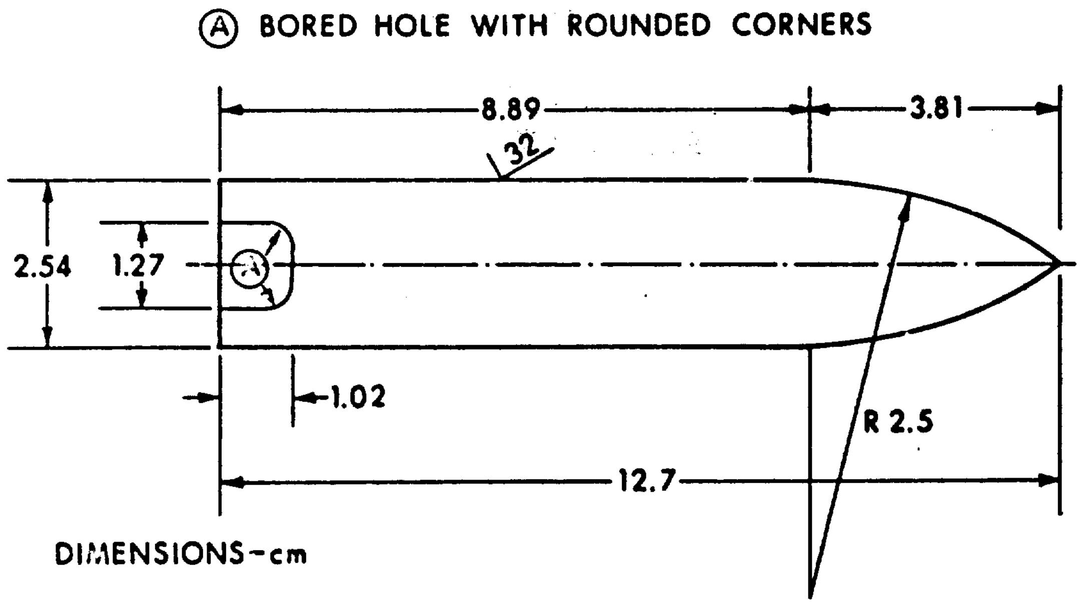
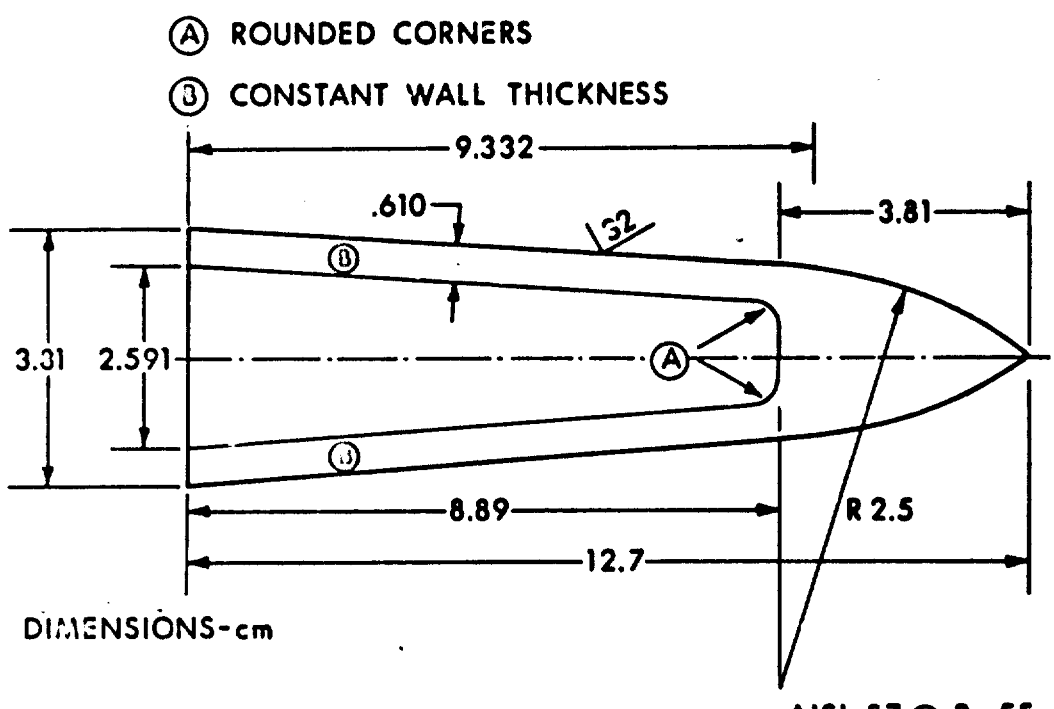
[1]*"Test Results of Earth Penetrators", Physics International Company, DNA Report 4180, December 1976.*



CYLINDRICAL DESIGN



TAPERED DESIGN

Figure 1. Schematic of Projectiles

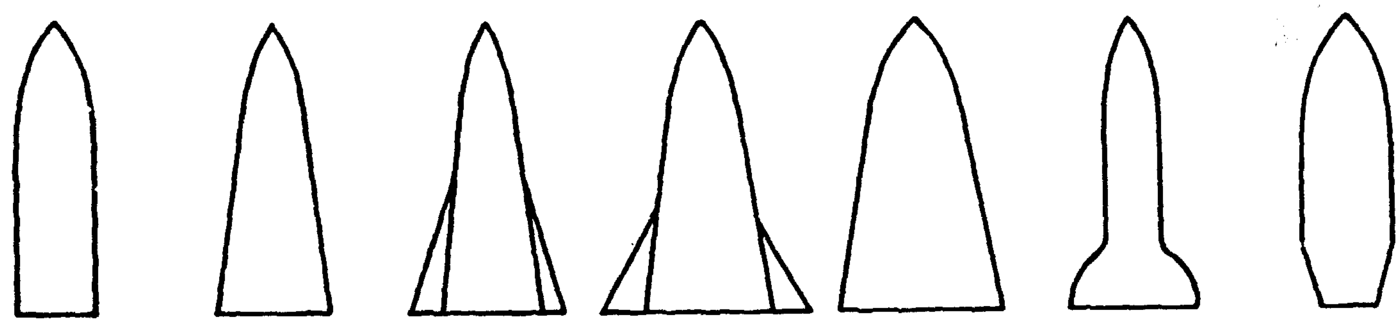


Figure 2. Designs Tested for DNA by Physics International

Table I. Projectile Physical Properties

Projectile	Round Number	Measured Mass (g)	Calculated Mass (g)	Calculated Center of Mass (cm from base)	Calculated Moment of Inertia Axial (gcm^2)	Calculated Moment of Inertia Transverse (gcm^2)
Cylinder	1	426	426	5.64	334	4440
	2	427				
	5	427				
	6	426				
	9	427				
	10	425				
	13	427				
	15	426				
Tapered	3	430	430	5.26	692	5070
	4	431				
	7	431				
	8	431				
	11	430				
	12	431				
	14	430				
	16	431				

III. SABOT DESCRIPTION

The sabot consisted of a carrier, a pusher plate, and an obturator. The carrier, Figure 3, was fabricated from polypropolux No. 944. The purpose of the carrier was to prevent balloting while passing through the gun tube. The carrier was designed to separate while in free flight. The pusher plate, Figure 4, was fabricated from 7075-T6 aluminum. The purpose of the pusher plate is to absorb the setback forces. The obturator, Figure 5, was fabricated from polypropolux No. 944. The purpose of the obturator was to provide a gas seal for the sabot assembly and to push the sabot assembly through the gun tube.

IV. TARGET

The target consisted of brick clay with 5cm (2 in.) of concrete facing. The concrete used in these tests consisted of the following mixture: 46.7kg (103 lbs.) of Type I Portland Cement; 170.6kg (376 lbs.) of concrete sand; and 26.8kg (59 lbs.) of water with 0.635cm diameter steel reinforcement, 15.24cm on centers at the centerline of the slab. The Corps of Engineers specified Type III Portland Cement to obtain an unconfined compressive strength of 27.6 MPa (4000 psi). Unfortunately Type I was used giving com-

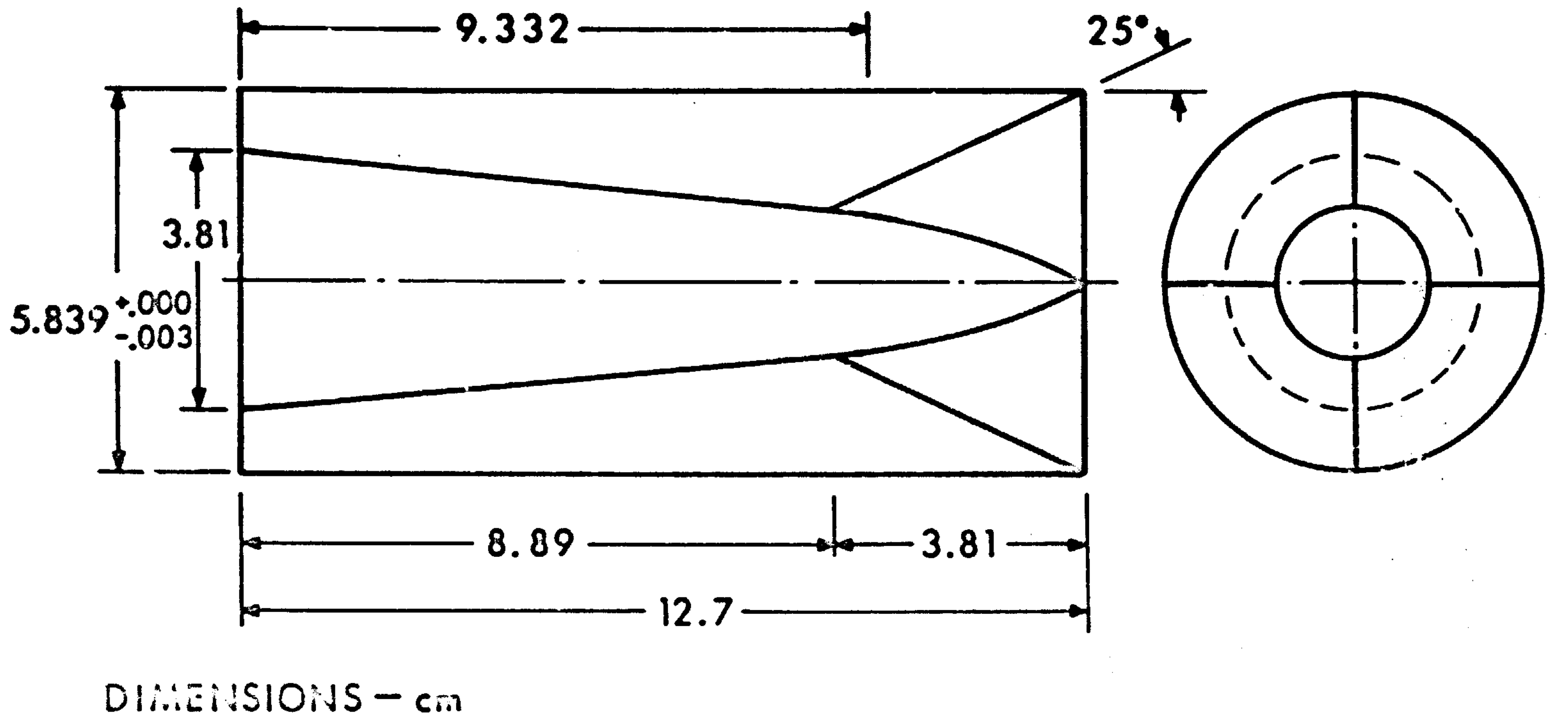


Figure 3. Carrier Design for Tapered Projectile, Polypropolux #944.

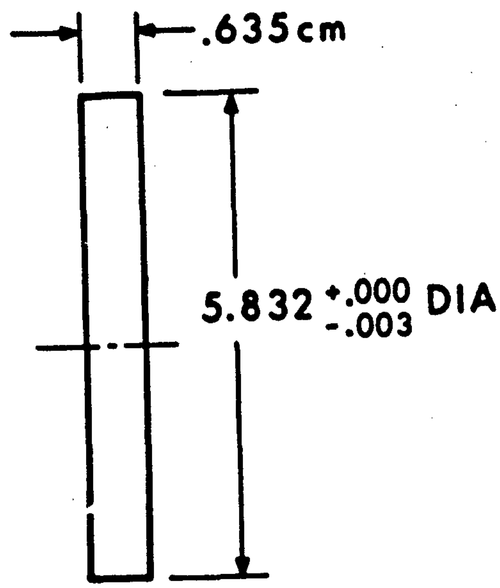


Figure 4. Pusher Plate Design, 7075-T6 Aluminum.

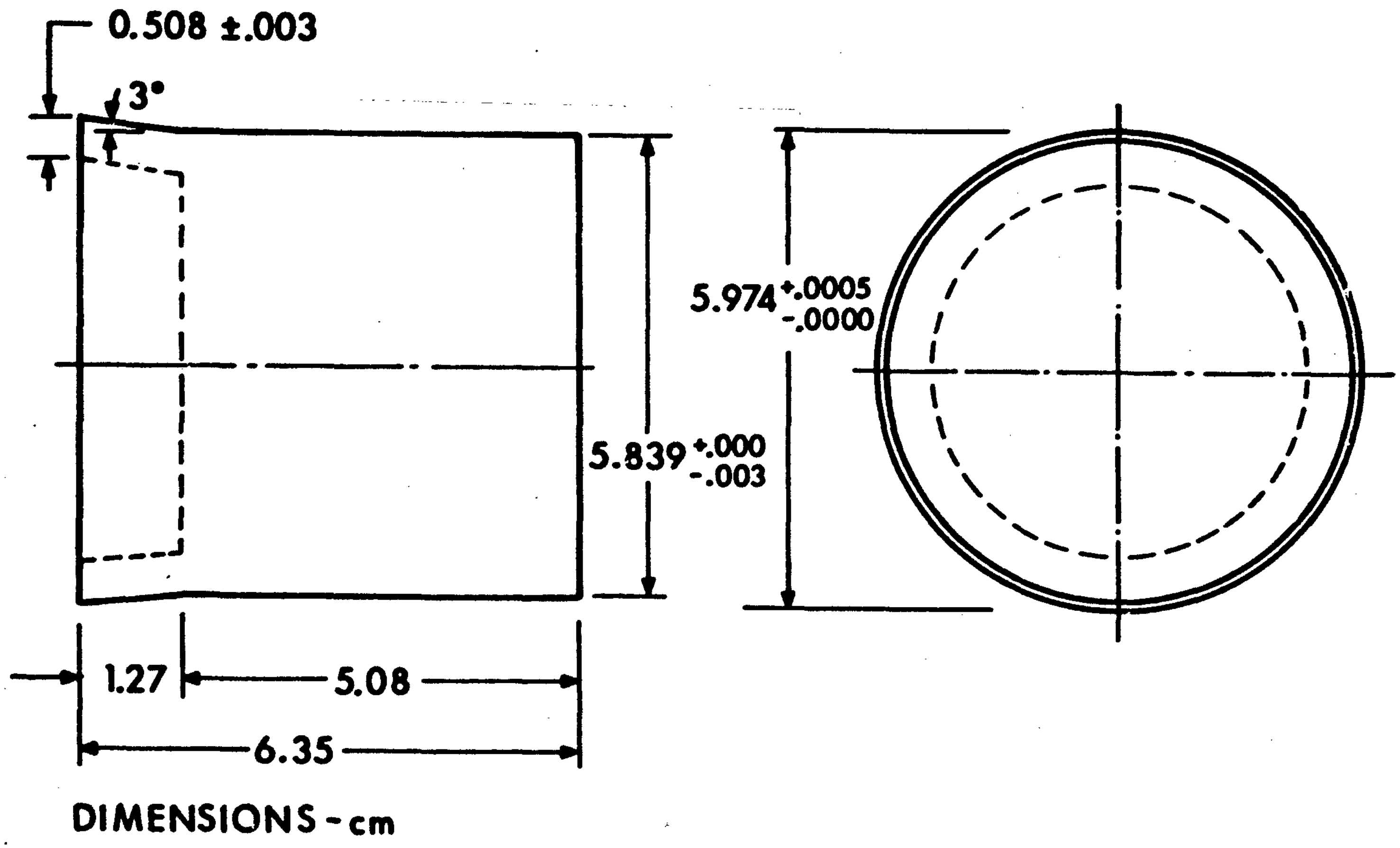


Figure 5. Obturator Design, Polypropolux #944.

pressive strengths generally (but not always) of one half that desired. However, the objective of the test was to determine projectile stability in soil hence it was decided to conduct the tests with the Type I concrete mixture. Table II gives the unconfined compressive strength, the date poured, and the date tested.

Table II. Concrete Target Data

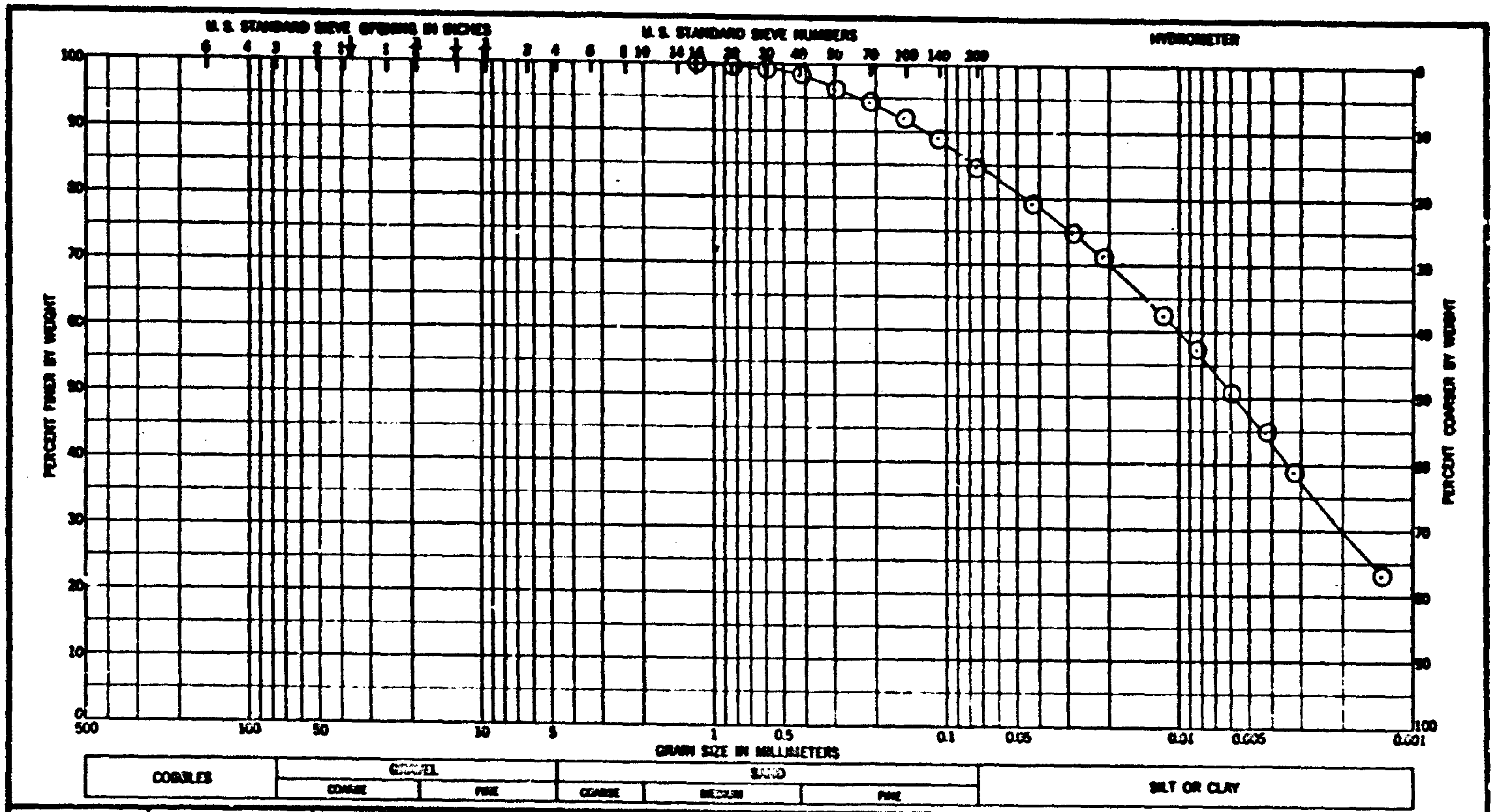
Date Poured	Specimen Number	Specimen Date Tested	Date of Test	Unconfined Compressive Strength (MPa)
16-12-77	1	12-1-78	24-1-78	14.3
16-12-77	2	12-1-78	26-1-78	25.4
15-12-77	3	31-1-78	27-1-78	12.5
15-12-77	4	31-1-78	31-1-78	16.9
17-12-77	5	23-2-78	2-2-78	10.0
17-12-77	6	1-3-78	3-2-78	10.9
17-12-77	7	3-2-78	10-2-78	27.0
17-12-77	8	8-2-78	14-2-78	19.5
19-12-77	9	15-2-78	16-2-78	31.2
17-12-77	10	15-2-78	22-2-78	18.3
19-12-77	11	17-2-78	23-2-78	10.0
17-12-77	12	1-3-78	28-2-78	13.7
19-12-77	13	8-3-78	2-3-78	10.6
20-12-77	14	8-3-78	3-3-78	13.5
20-12-77	15	10-3-78	6-3-78	13.5
20-12-77	16	10-3-78	7-3-78	15.4

Two samples of the clay were sent to the Corps of Engineers for gradation test. Figure 6 shows the results of the test. The size of the concrete face was 122cm x 122cm x 5.08cm and the size of the clay portion was 122cm x 122cm x 500cm. The clay was tamped before each test. Figure 7 shows the concrete/clay target placement in the experimental set-up.

V. EXPERIMENTAL SET-UP

Figure 8 shows a schematic of the experimental test set-up. X-ray sources were used to record the event. Two were situated to provide orthogonal views of the projectile just prior to impact to obtain position and orientation of the projectile. The third source was located 46cm ahead of the orthogonal station to provide an additional position point for estimating striking velocity[2].

[2] *"X-ray Multi-Flash System for Measurement of Projectile Performance at the Target", C. L. Grabarek and E. L. Herr, Ballistic Research Laboratories Technical Note 1634, September 1966.* (AD #807619)



Sample No.	Elev or Depth	Classification	Nat w %	LL	PL	PI	Project BRICK CLAY
JARS 1 & 2		SANDY CLAY(CL) RED					Area
		Gs= 2.70(est)					Boring No.
							Date 24 JAN 78

GRADATION CURVES

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Figure 6. Gradation Curves and Specific Gravity

Figure 7. Concrete/Clay Target Placement in the Experimental Set-up

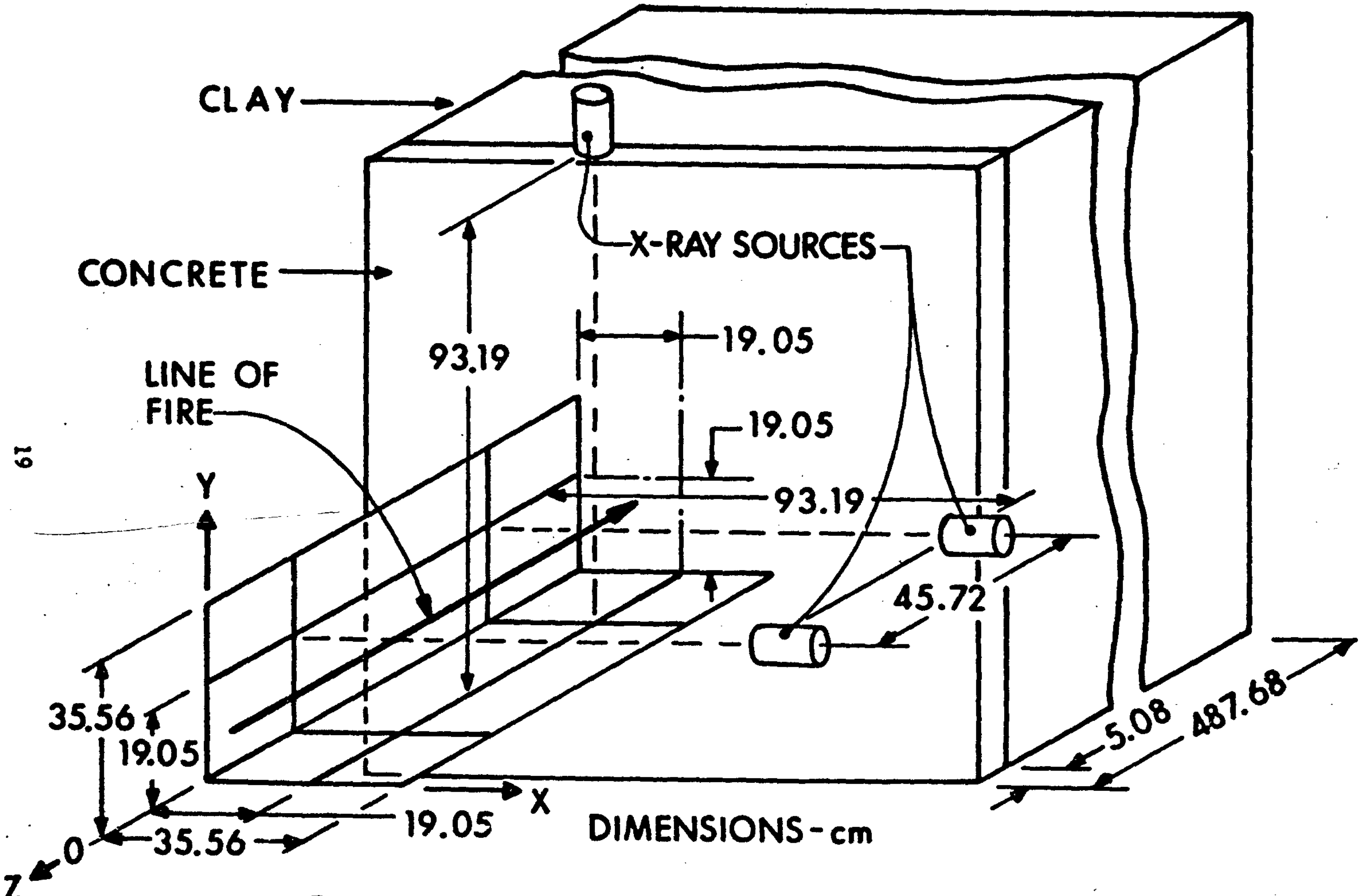

Figure 8. Schematic of Experimental Set-Up

The time lapse between the two x-ray flashes was preset commencing when the projectile passed through a trigger screen placed uprange and in the path of the projectile. Figure 9 shows a typical photograph of the dynamic event.

VI. TEST MATRIX

Table III shows the test matrix. The striking velocities and obliquities chosen by the DNA reflect impact conditions of certain weapons systems. Controlled angles of attack of 0° and 3° were considered, but such control is very difficult and expensive. Thus, the orientation of the projectile was not controlled, but measured for each test.

Table III. Test Matrix

Projectile Type	Striking Velocity (m/s)	Target Obliquity (deg)
A	305	0
A	305	20
A	305	0
A	305	15
A	305	15
A	610	0
A	610	0
A	610	20
B	305	0
B	305	0
B	305	20
B	305	15
B	305	15
B	610	0
B	610	0
B	610	20

A - cylindrical
B - tapered

VII. ANALYSIS

Self-foaming polyurethene, type PE2, manufactured by the WITCO Chemical Corporation was pumped into the clay cavity. The foam is a mixture of equal portions of two liquids, PE-2A and PE-2B of chemical composition known only to the manufacturer. The foam solidifies in a few minutes. The mold was recovered by removing the clay.

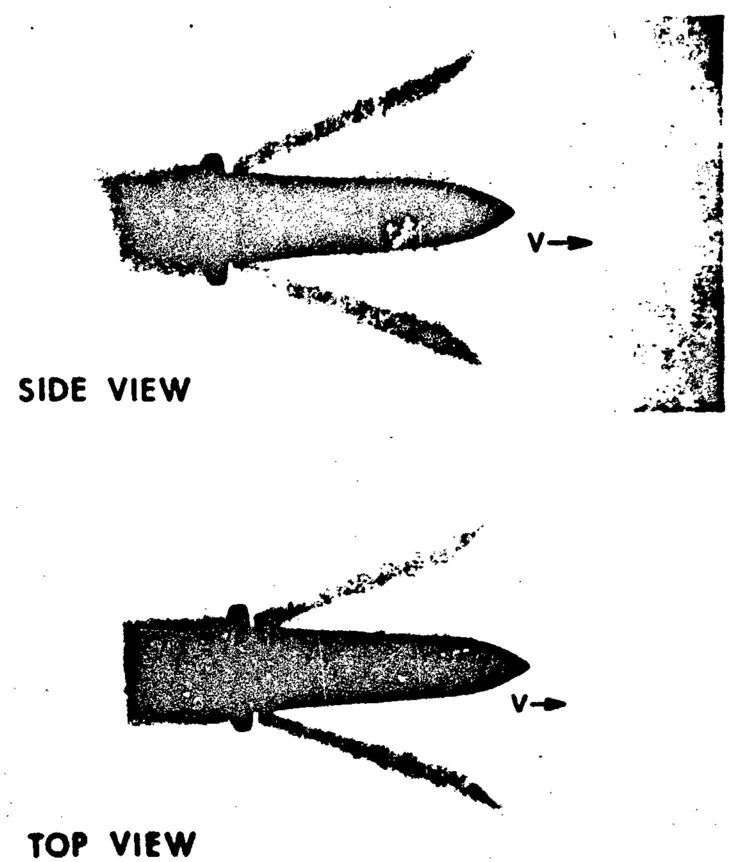

Figure 9. Orthogonal Views of Sabot Separating from Tapered Projectile.

The position of the center of the cavity is measured using a plumb line to the top of the cavity and adding the approximate radius of the cavity. These measurements, giving horizontal and vertical positions, were taken every 15.24cm (6 in.) of penetration along the line of sight.

From firings into other dense nonmetallic media[3], it has been learned that non-deforming gyroscopically unstable projectiles penetrate a short distance before the onset of catastrophic growth in yaw (projectile tumble). The deviation from a straight line penetration path arises from the lift force induced by yaw. This force will be proportional to the sine of yaw up to 20 degrees or so. Therefore, we expect the lateral deviation of the penetrator from the line of sight path (swerve) to be proportional to the second integral of yaw. Since the growth of yaw is essentially exponential for yaws to 20 degrees, the second integral of yaw and, hence, the swerve are also exponential from the onset of tumble. Thus, when comparing gyroscopically unstable motions of different projectile designs, the size of swerve at onset of tumble is proportional to the size of the lift force and the log of the percentage growth in swerve during tumble is proportional to the square root of the overturning moment coefficient (slope of the overturning moment vs. yaw curve). Hence, we should expect a larger lift force for the same yaw for the tapered projectile because the cross section at that position where cavitation begins will be larger than that for the cylindrical projectile. On the other hand, the overturning moment and the percentage growth in swerve can be reduced by tapering if the rearward shift in initiation of cavitation is sufficiently large (past the center of mass) to reduce the lever arm of the moment significantly.

To analyze the measurements, we separated the event into two stages; trajectory prior to impact and trajectory through the soil, or before and after the concrete face. This procedure identifies the deflection, if any, due to concrete penetration and the stability of the design in clay given an entrance path.

The deflection through the five-centimeter concrete face amounted on the average to displacements of 4mm to the right looking downrange and 13mm down. The deflections from line of sight computed for such displacements are larger than those estimated for the initial paths in clay. We conclude that the jump conditions result in deflecting the penetrator, therefore the pre-impact positions cannot be used as the line of sight survey to the clay position measurements, but only for estimating the striking velocity.

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[3]*"Stability of Penetrators in Dense Fluids", E. T. Roecker and A. J. Ricchiazzi, Proceedings of the 14th Annual Meeting of the Society of Engineering Science Inc., Lehigh University, Bethlehem, PA, November 1977.*

The coordinate system for the clay measurements was such that z was directed along the line of sight, y was vertical, and x completed the orthogonal system. We chose the initial tangent to the trajectory in clay as the effective line of sight, the p direction, to free our clay data from concrete effects in order to analyze more properly the stability of the projectiles in clay. The lateral displacement from the p-axis becomes the swerve and is called r. The swerve vs. effective line of sight distances for the rounds are given in Figures 10 through 24.

Examination of these swerves showed that the penetration path was a straight line along the effective line of sight until some position where marked deviation took place. This position we infer to be the onset of large yaw growth. We separated the motion into two parts: the initial straight line path and the departure with rapid growth of swerve, i.e., before and after onset of large yaw growth.

The length of the straight line path is a function of striking yaw, as well as yawing velocity to some extent; of projectile design; and of random conditions during transition from air to full immersion in the clay. With the exception of projectile design these variables were not controlled in the experiment. Where relatively larger striking yaw was encountered, it can clearly be seen that a very short length of straight line path exists, Figure 25. For the most part, therefore, the length of the straight line path is a function of impact conditions (primarily striking yaw) and other stochastic variables. Since these variables are not particularly related to projectile design, we turn to the deviation portions of the trajectories for our stability comparisons*.

To examine the effect of target obliquity, we superimposed the rapid growth in swerve portions of the trajectories. These superpositions, shown in Figures 26 through 29, reveal that the 0 to 20 degree obliquity of this experiment did not alter the swerve vs. effective line of sight data although rounds 1, 12, and 16 did not superimpose upon their colleagues. Rounds 1 and 12 we assume to be spurious. Round 16 was fired at 20° obliquity while the other tapered, high velocity rounds, 7 and 8, were at 0° obliquity. We disregard this as an obliquity effect since the other categories: tapered, low velocity; cylindrical, low velocity; and cylindrical, high velocity show no obliquity effect. Round 16 joins rounds 1 and 12 as mild deviants.

**It is expected that any design with reduced instability after onset of rapid yaw growth will also tend to increase the length of the straight line portion, other variables being equal. Hence, this tack is conservative.*

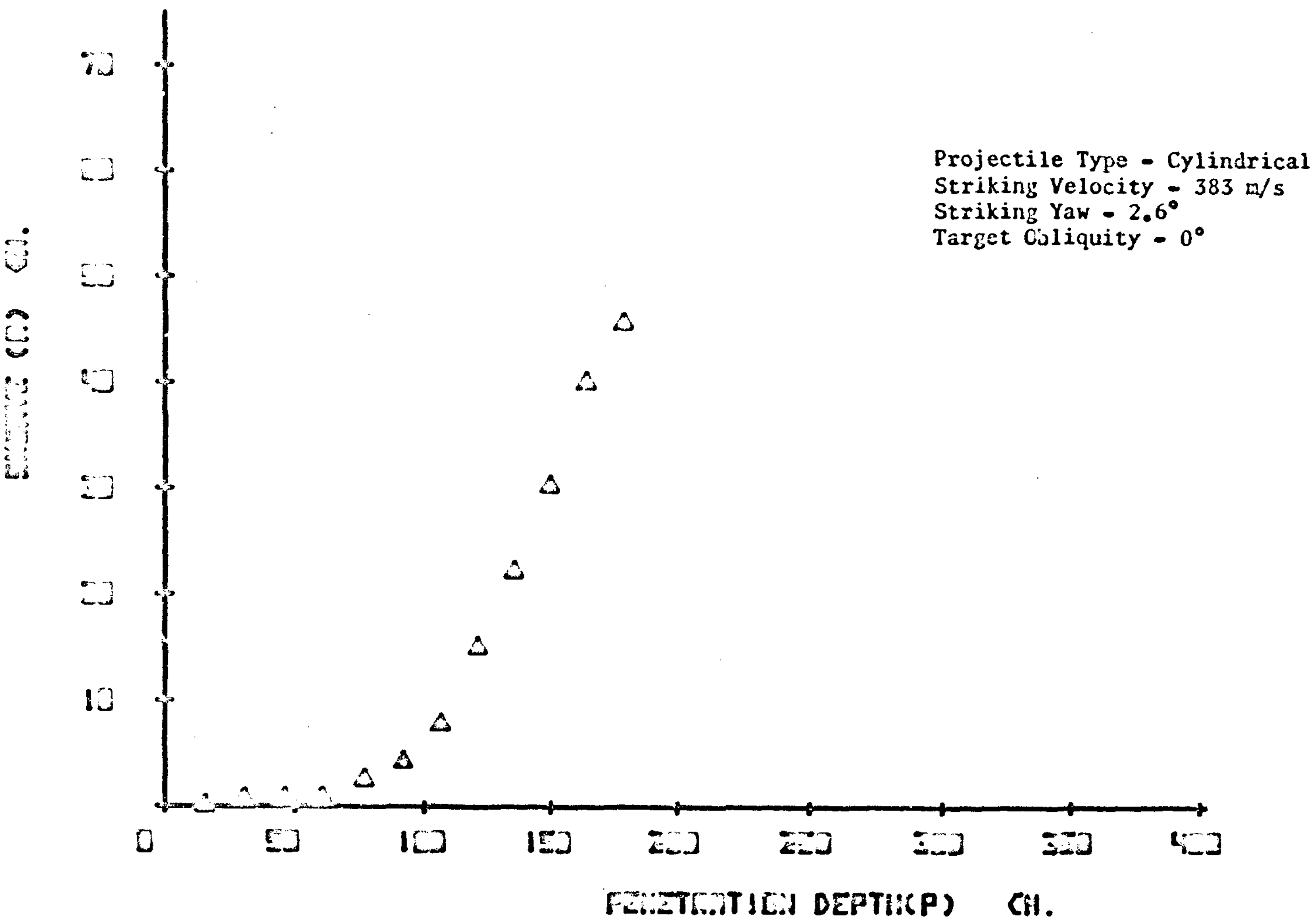

Figure 10. Swerve vs. Penetration Depth for Round 1

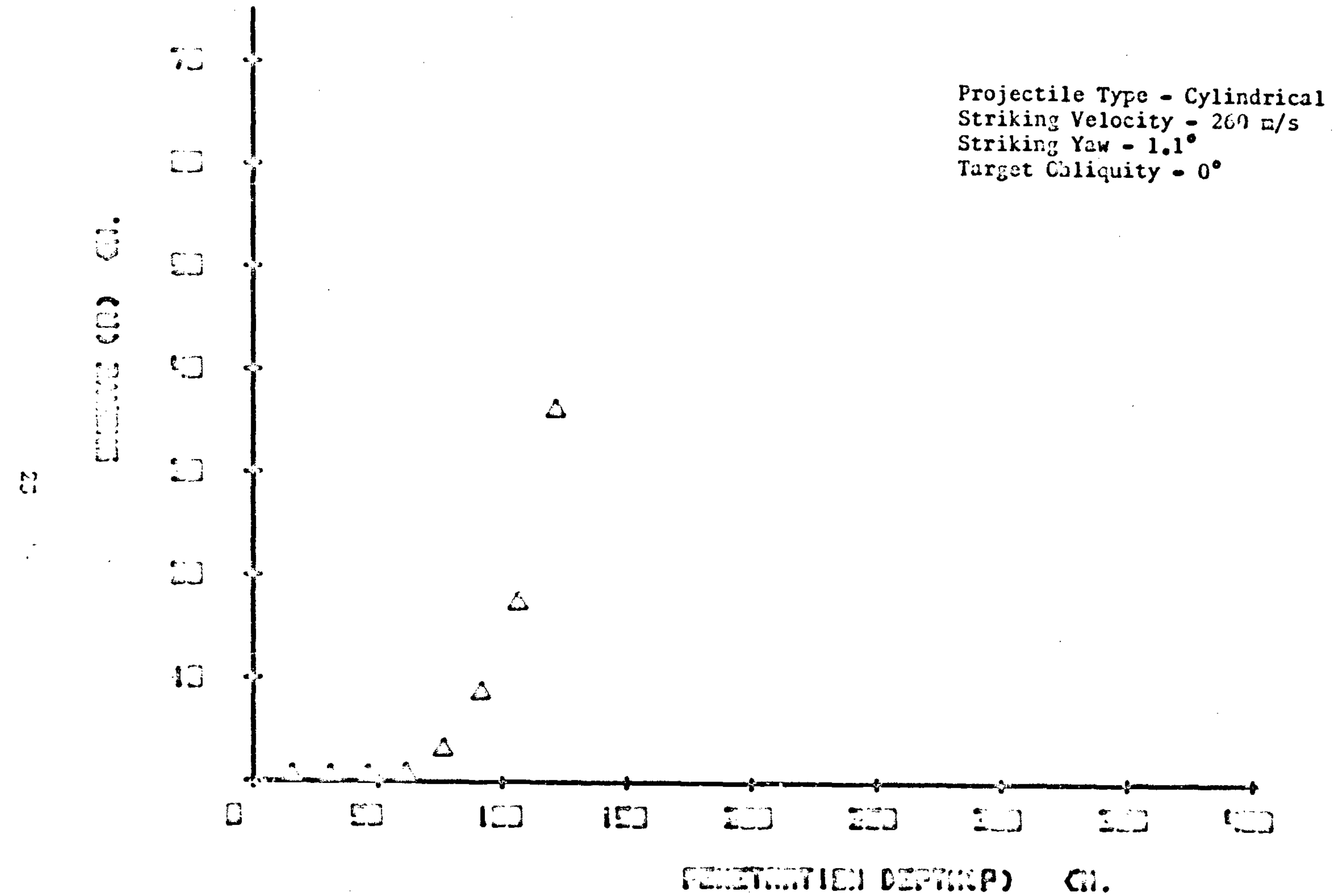

Figure 11. Swerve vs. Penetration Depth for Round 2

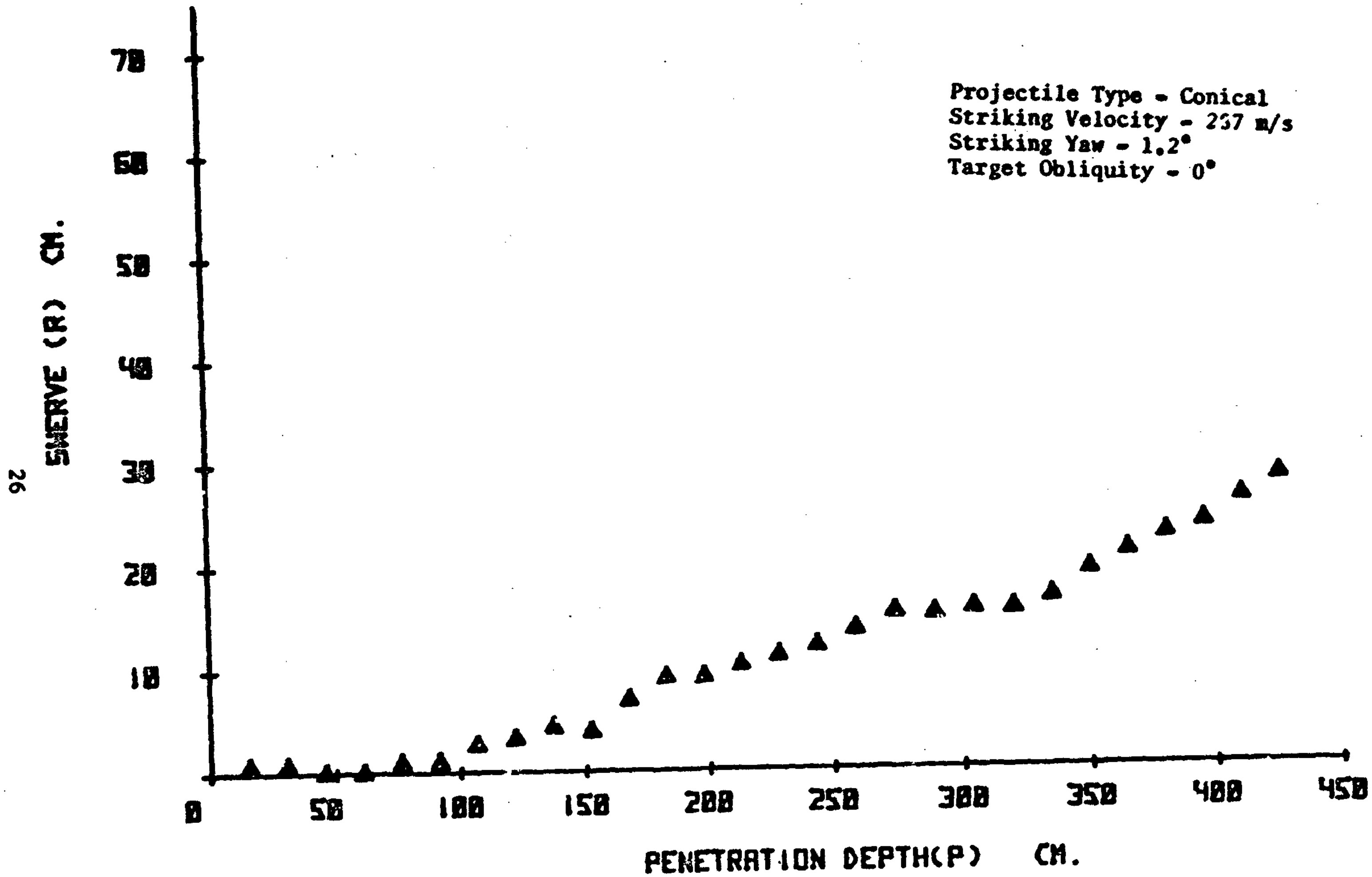

Figure 12. Swerve vs. Penetration Depth for Round 3

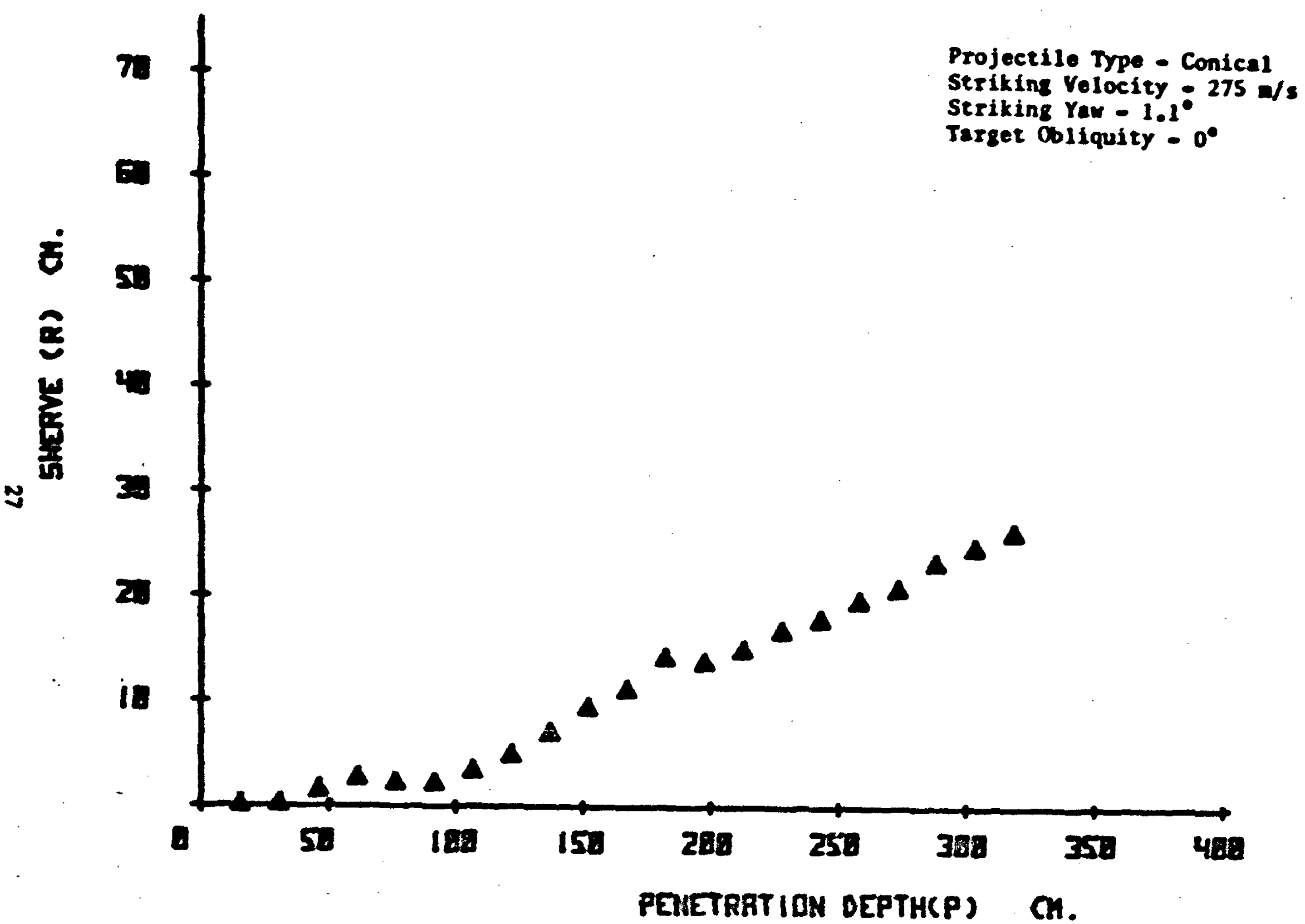

Figure 13. Swerve vs. Penetration Depth for Round 4

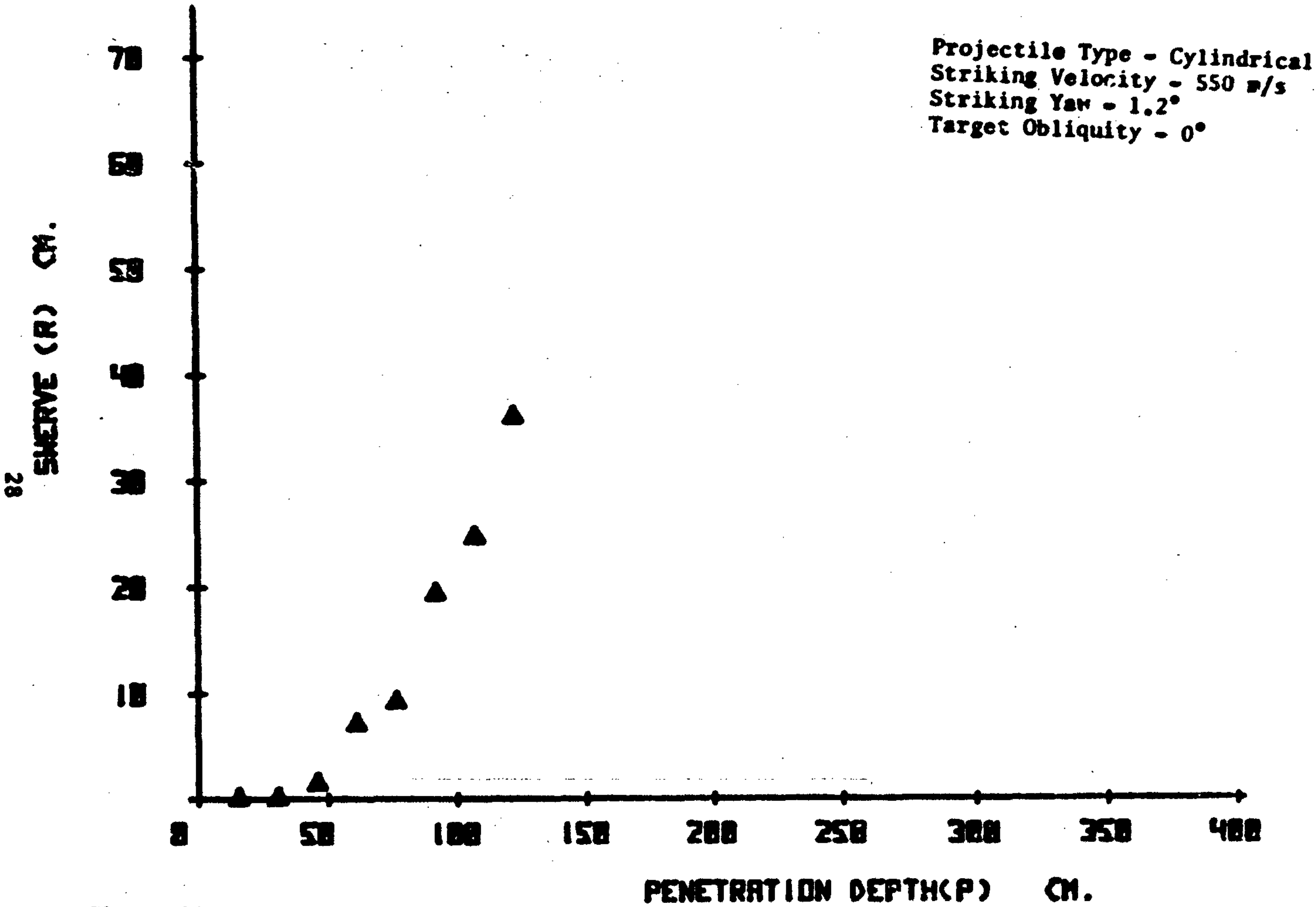

Figure 14. Swerve vs. Penetration Depth for Round 5

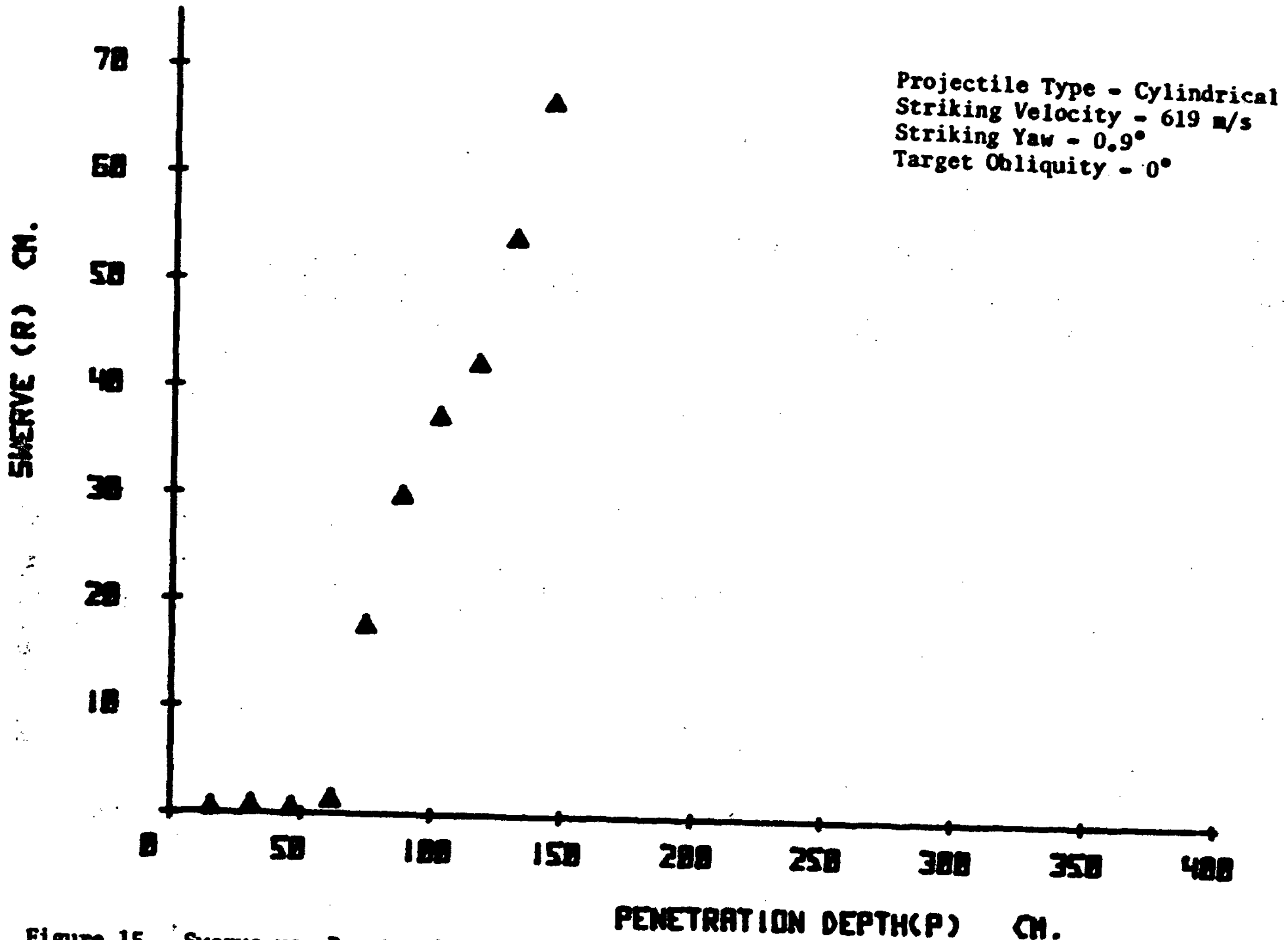

Figure 15. Swerve vs. Penetration Depth for Round 6

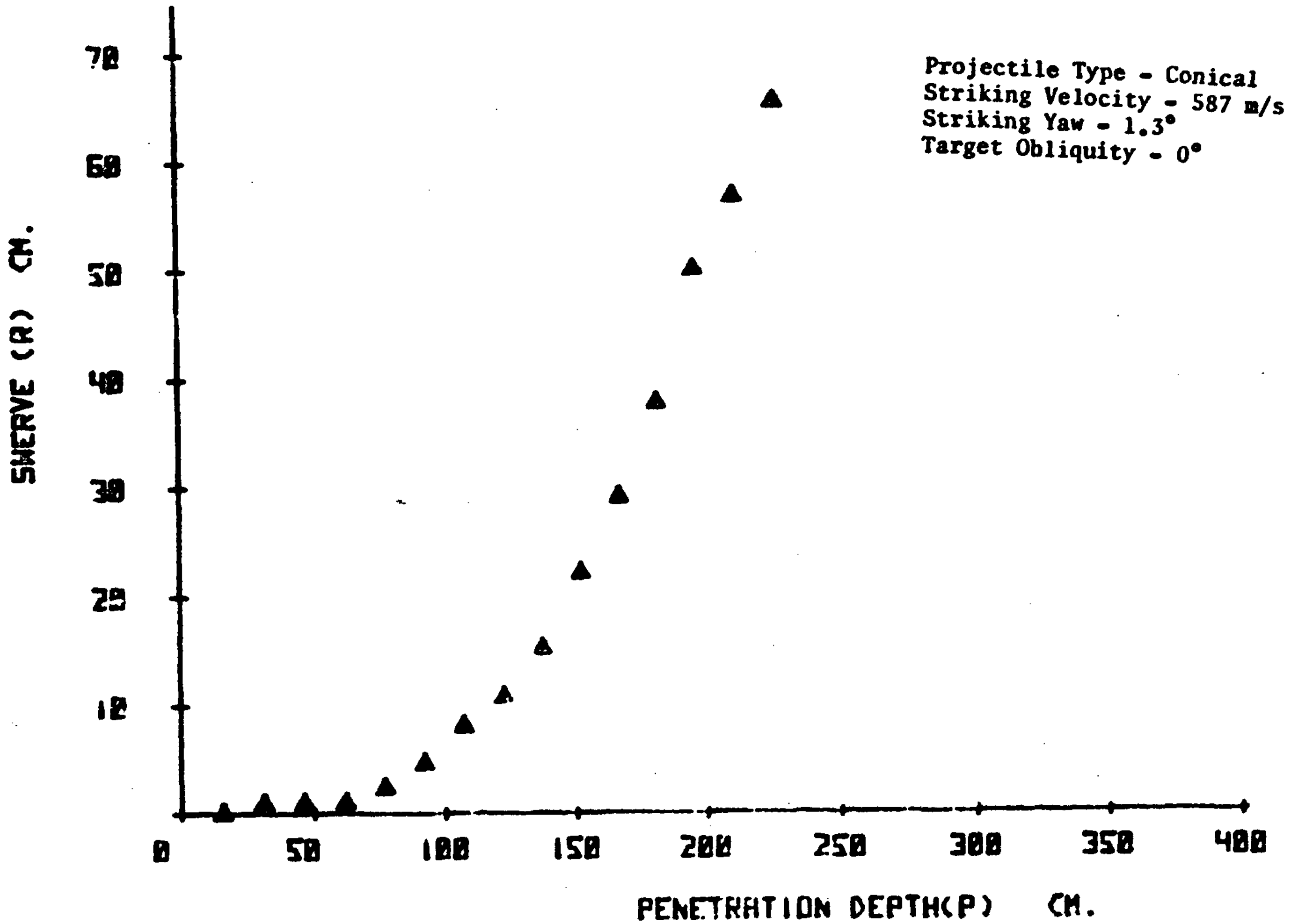

Figure 16. Swerve vs. Penetration Depth for Round 7

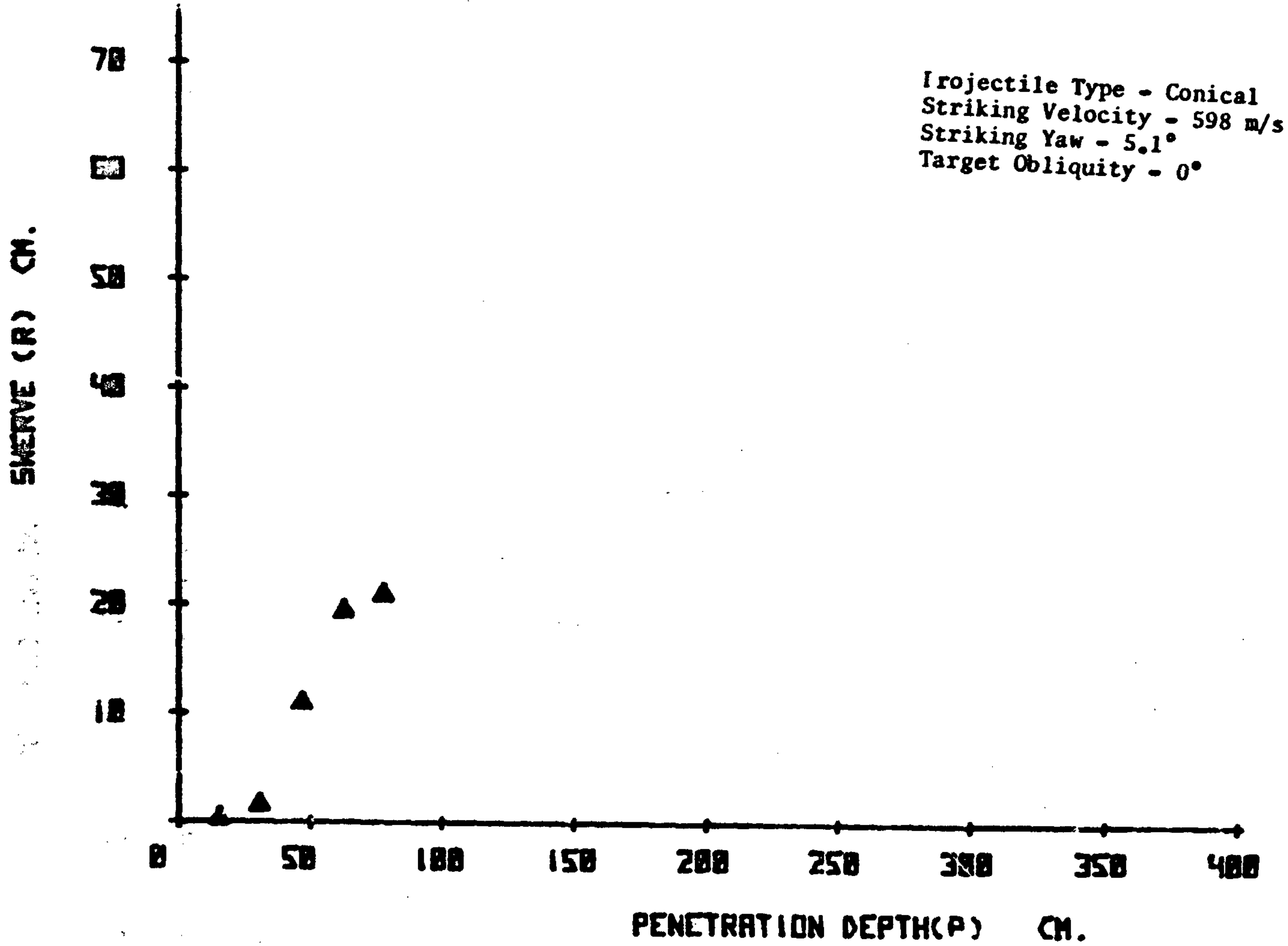

Figure 17. Swerve vs. Penetration Depth for Round 8

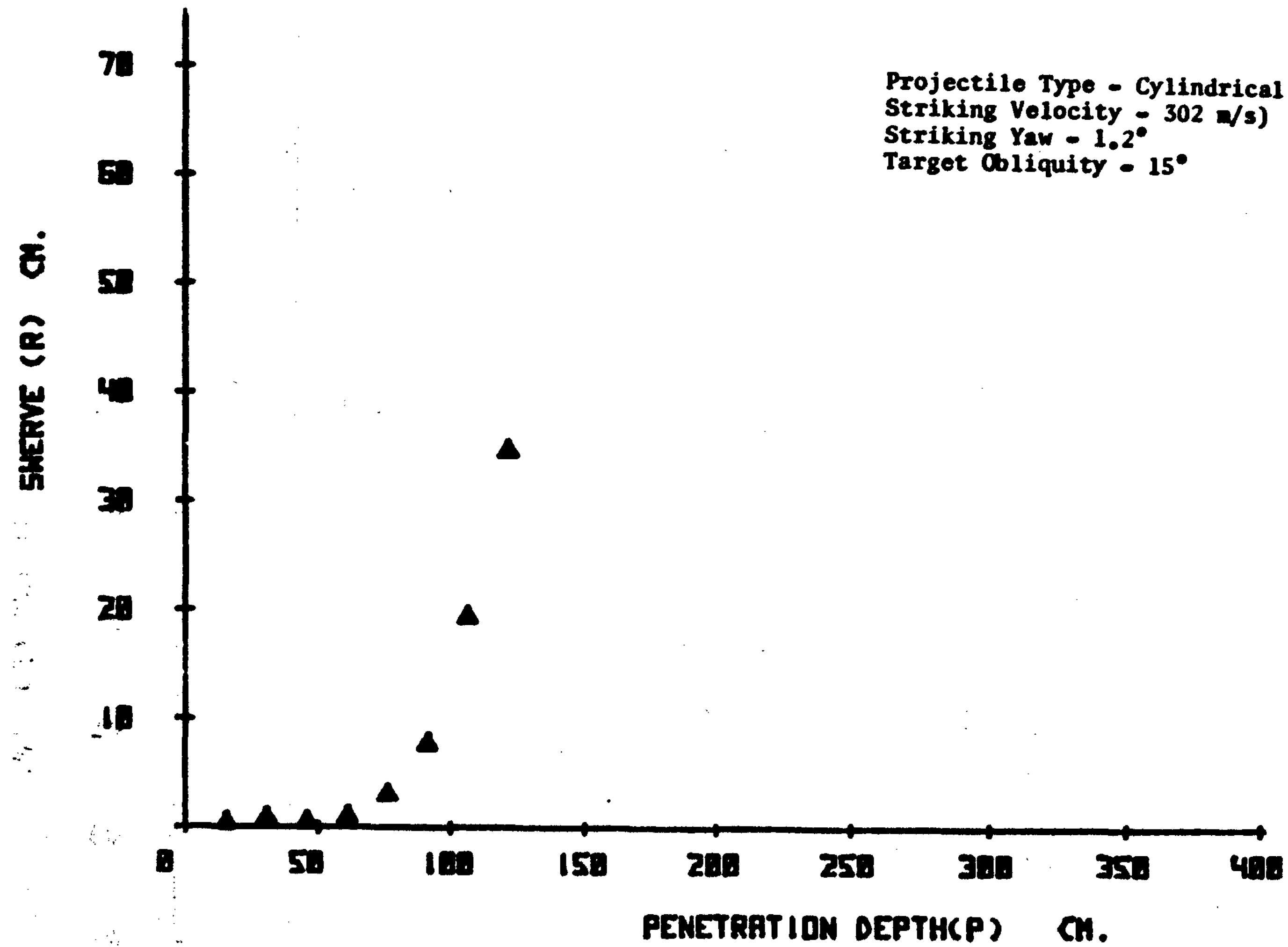

Figure 18. Swerve vs. Penetration Depth for Round 9

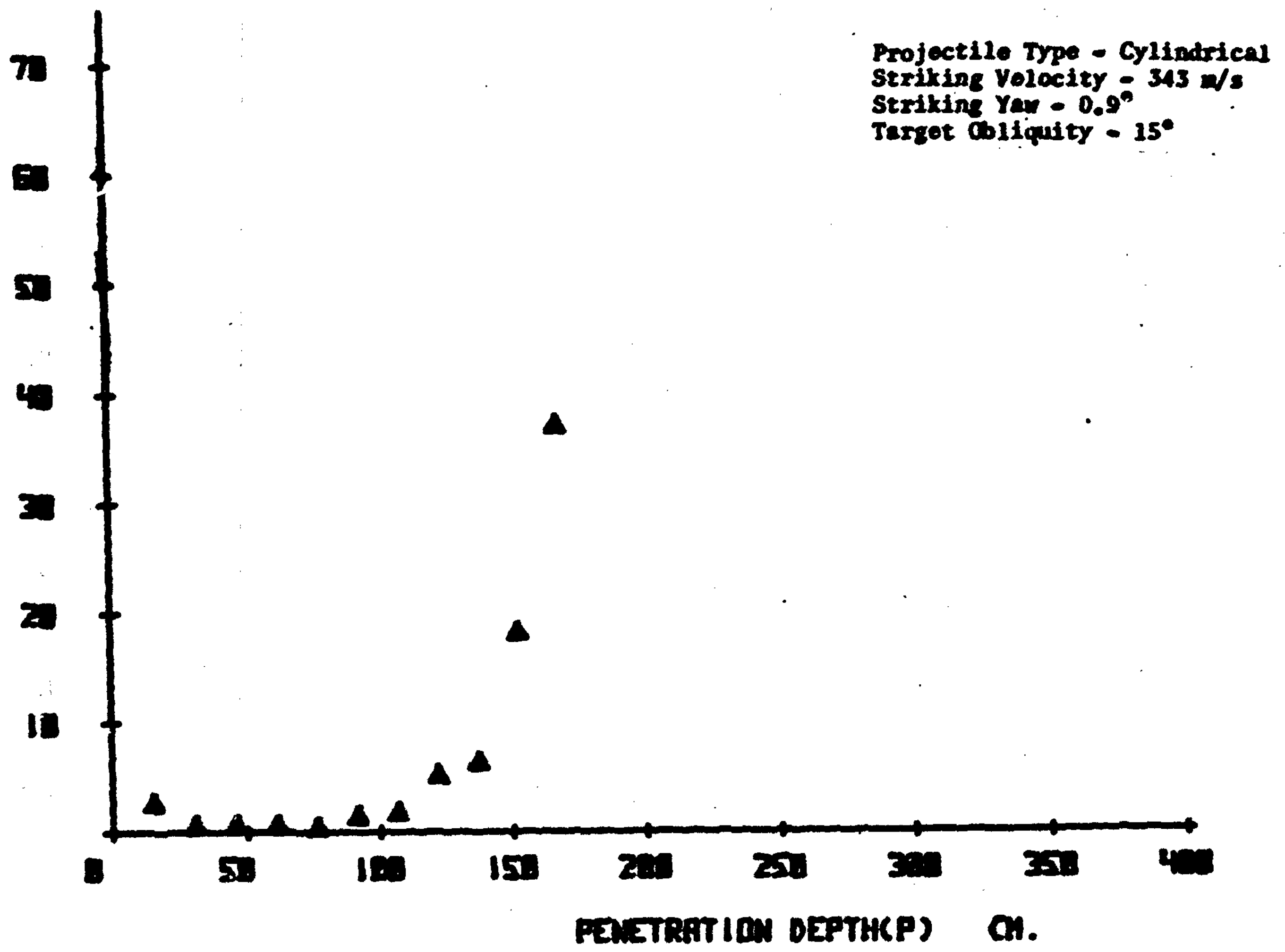

Figure 19. Swerve vs. Penetration Depth for Round 10

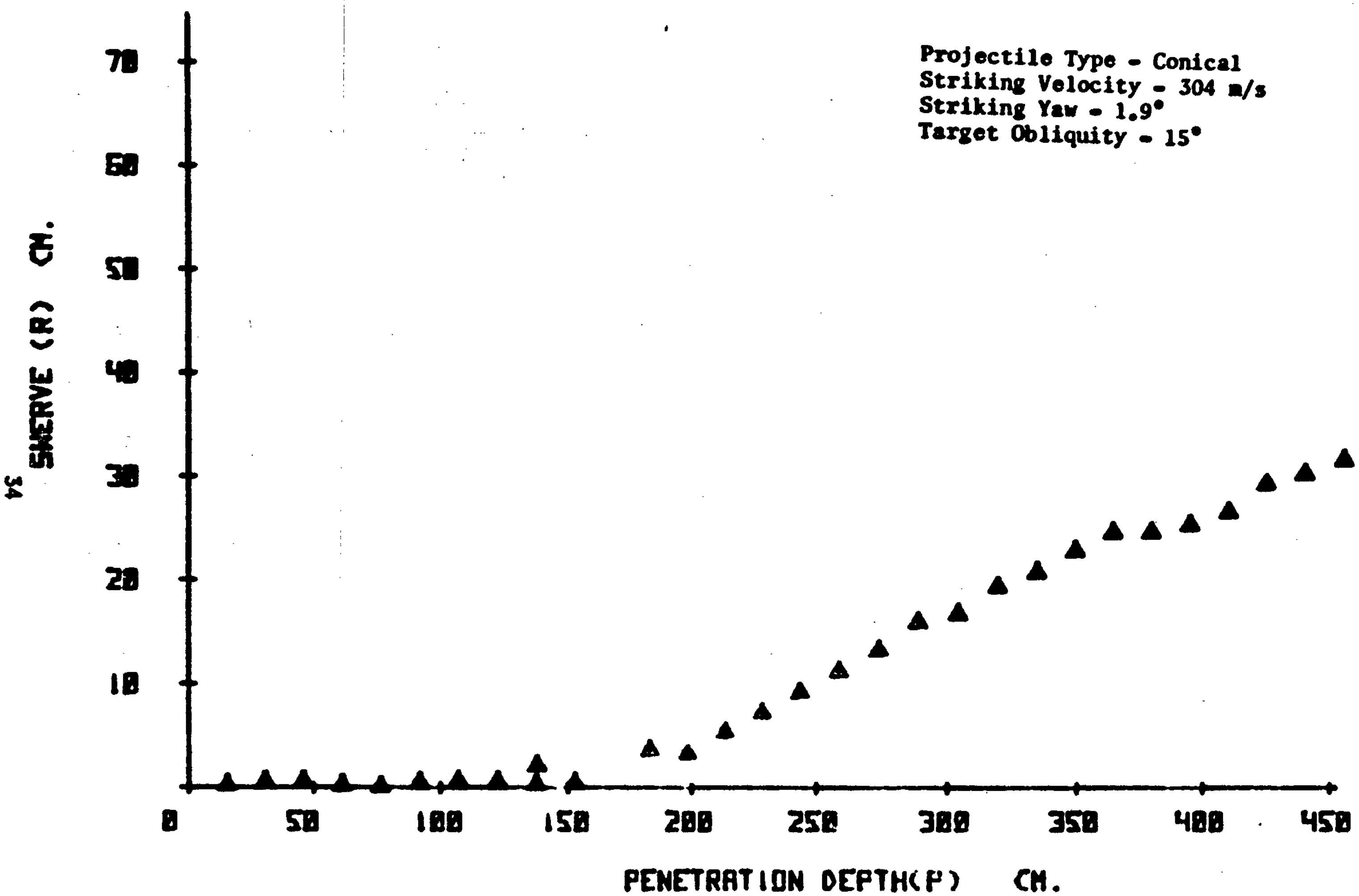

Figure 20. Swerve vs. Penetration Depth for Round 11

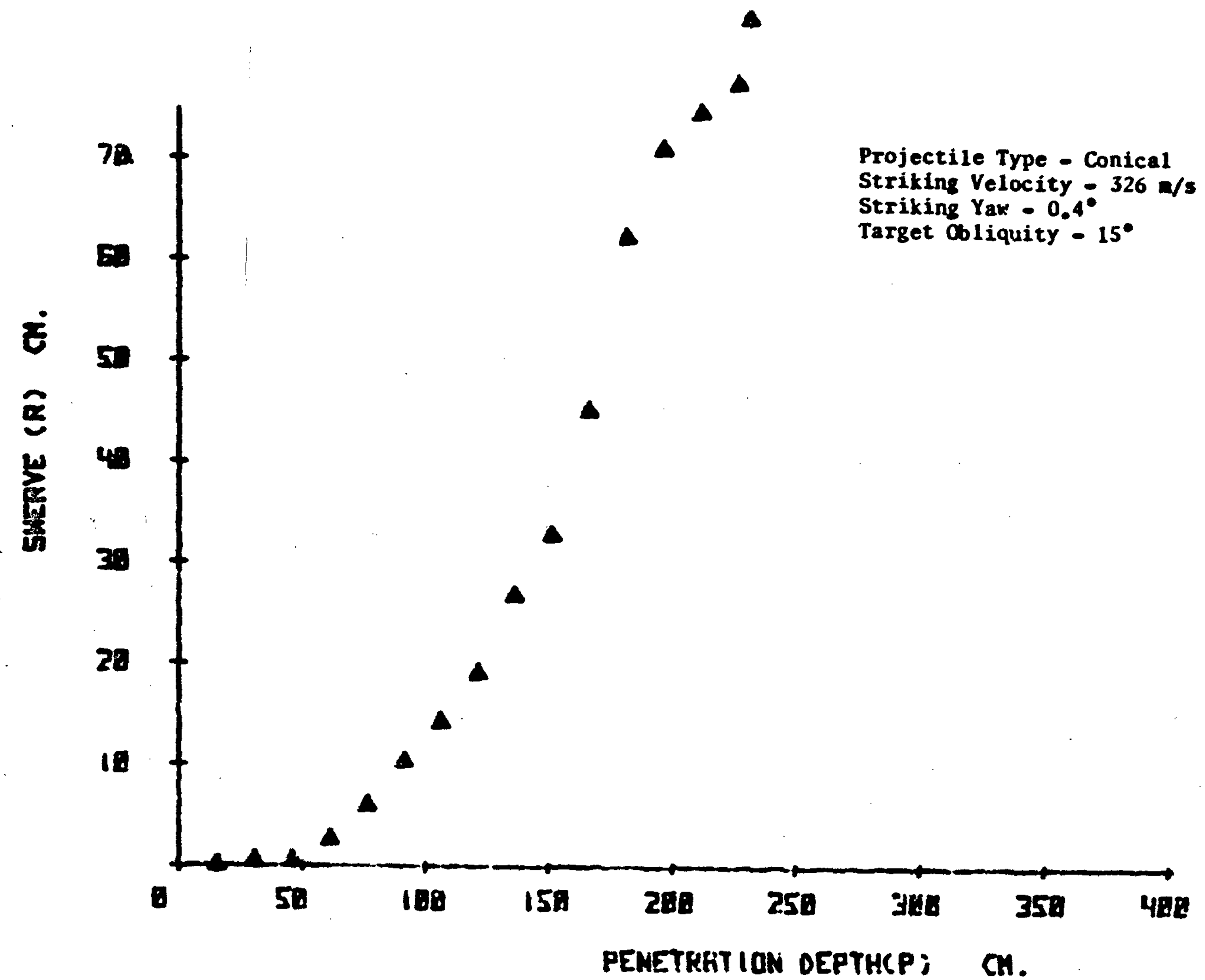

Figure 21. Swerve vs. Penetration Depth for Round 12

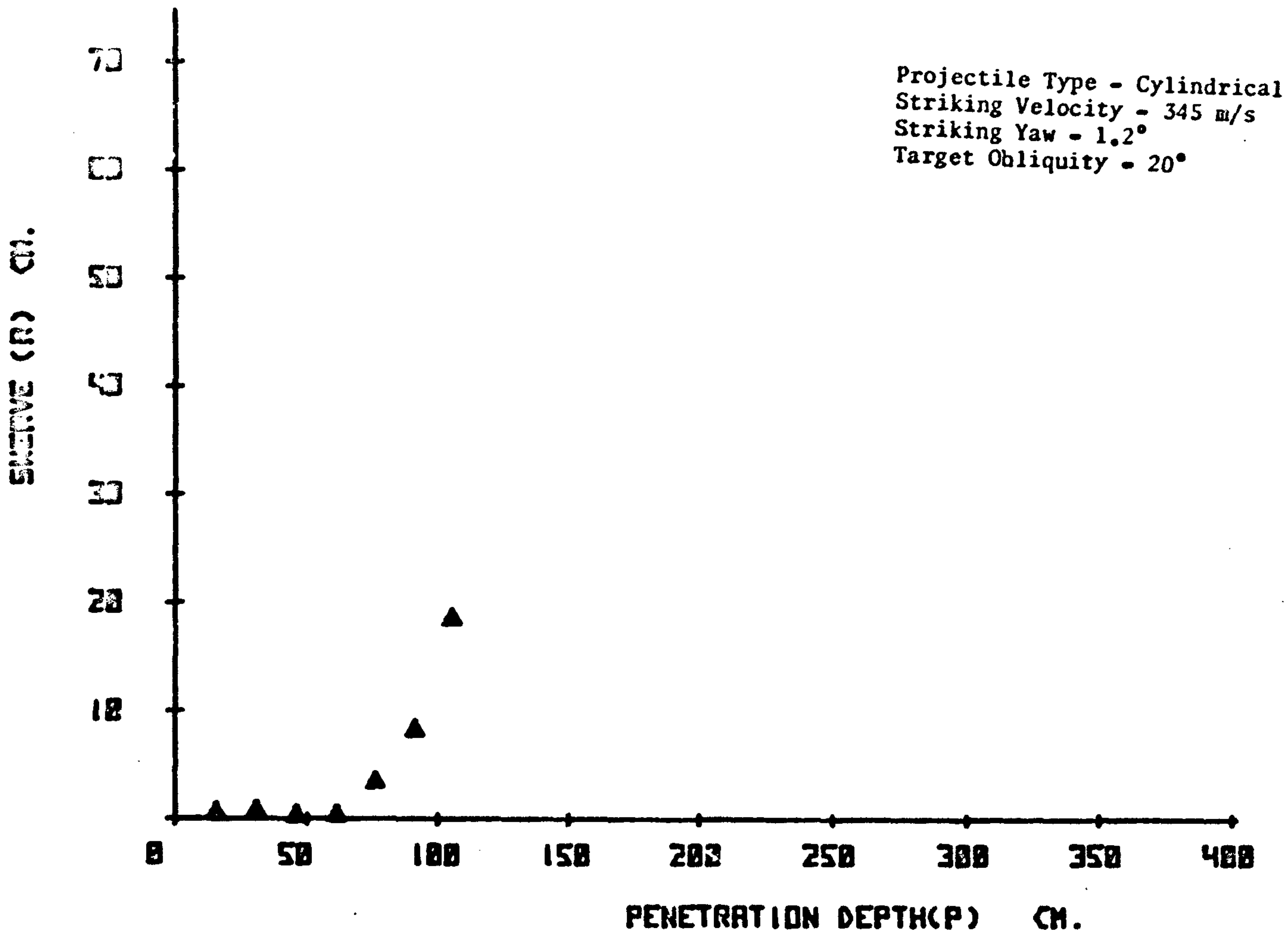

Figure 22. Swerve vs. Penetration Depth for Round 13

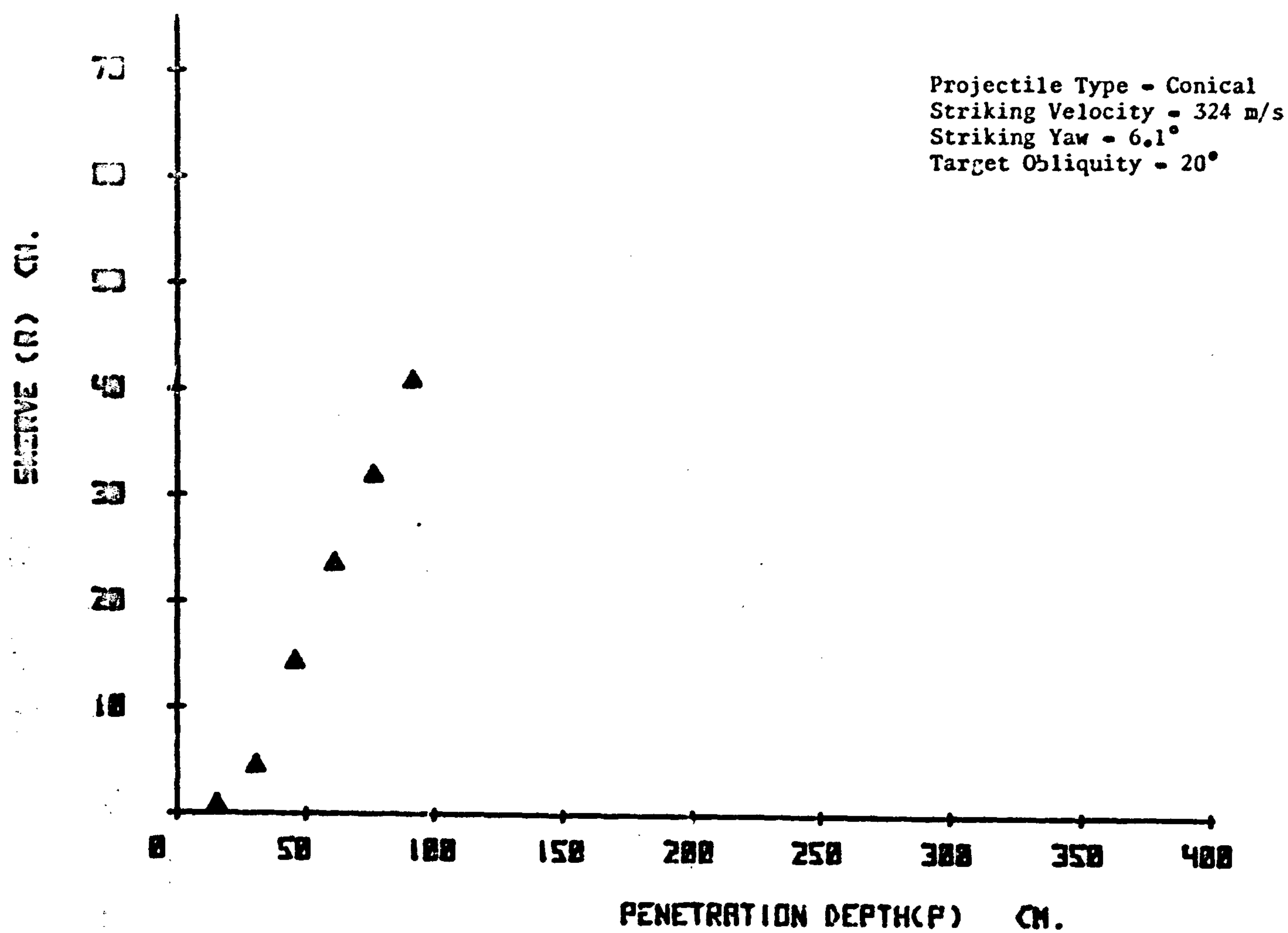

Figure 23. Swerve vs. Penetration Depth for Round 15

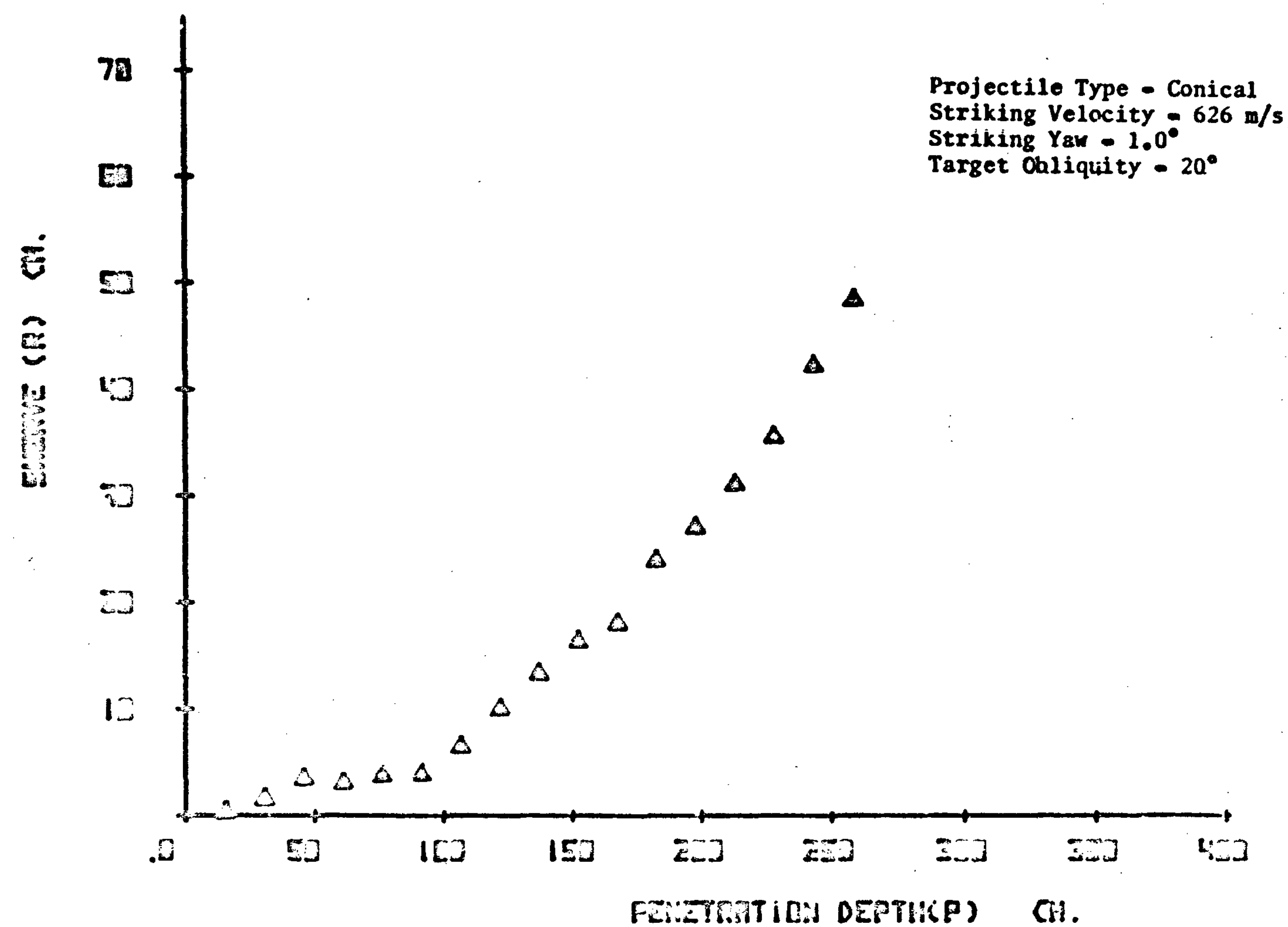

Figure 24. Swerve vs. Penetration Depth for Round 16

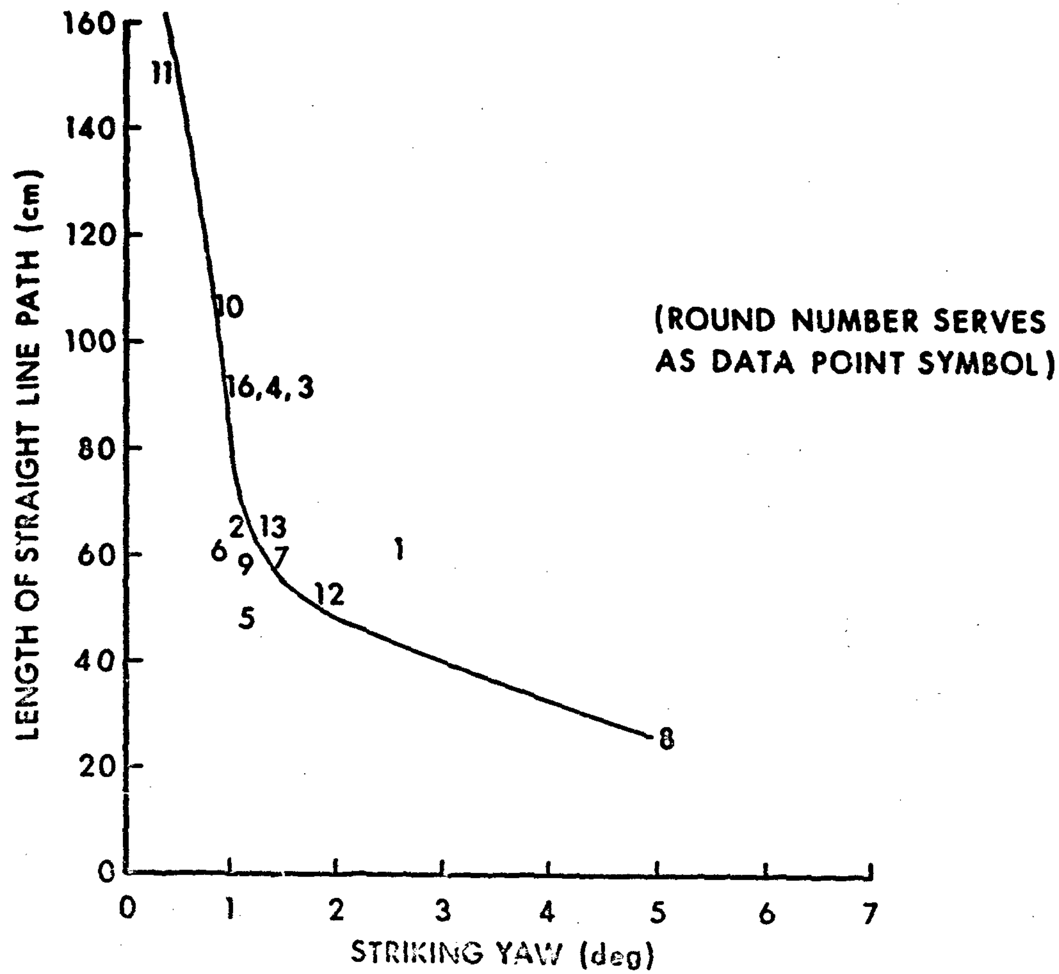

Figure 25. Length of Straight Line Path vs. Striking Yaw

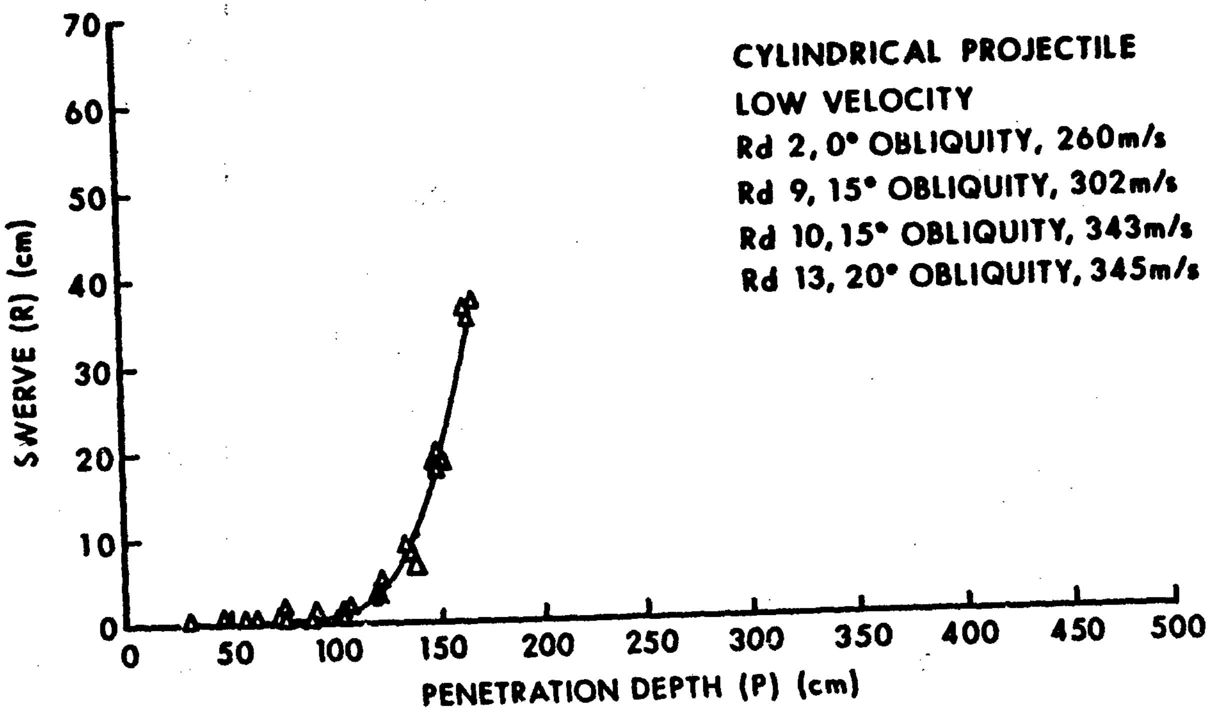

Figure 26. Swerve vs. Penetration Depth, Combined Cylindrical Projectile, Low Velocity Rounds

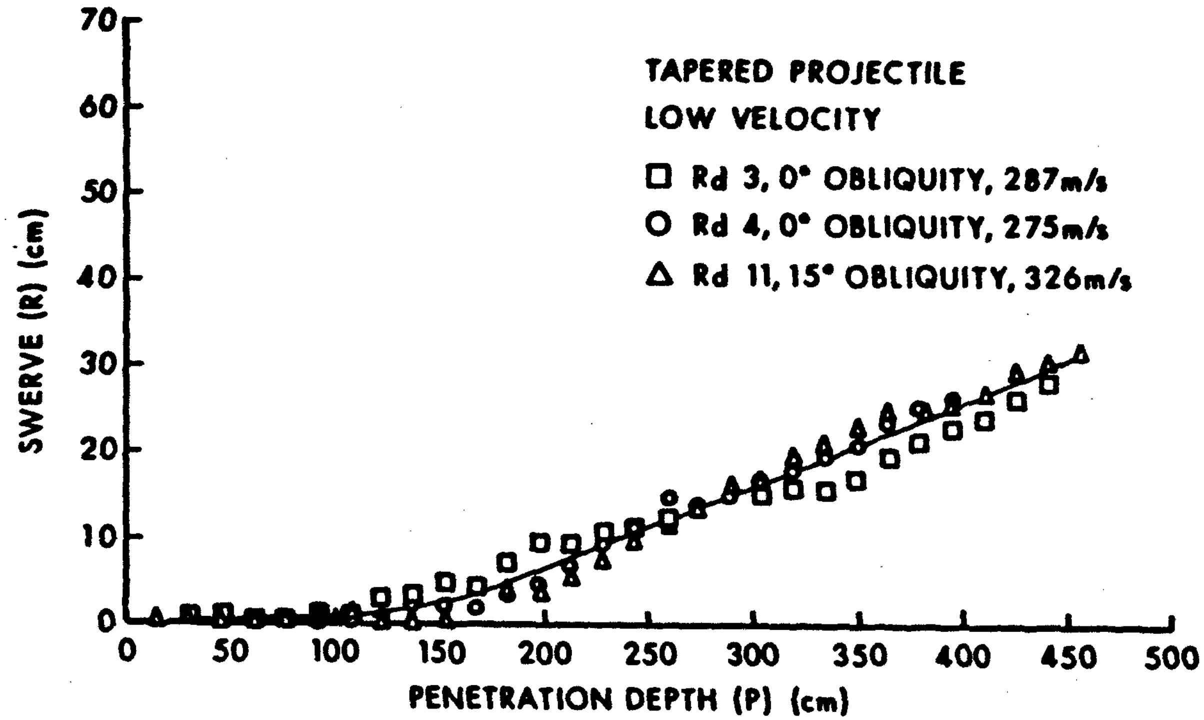

Figure 27. Swerve vs. Penetration Depth, Combined Tapered Projectile, Low Velocity Rounds

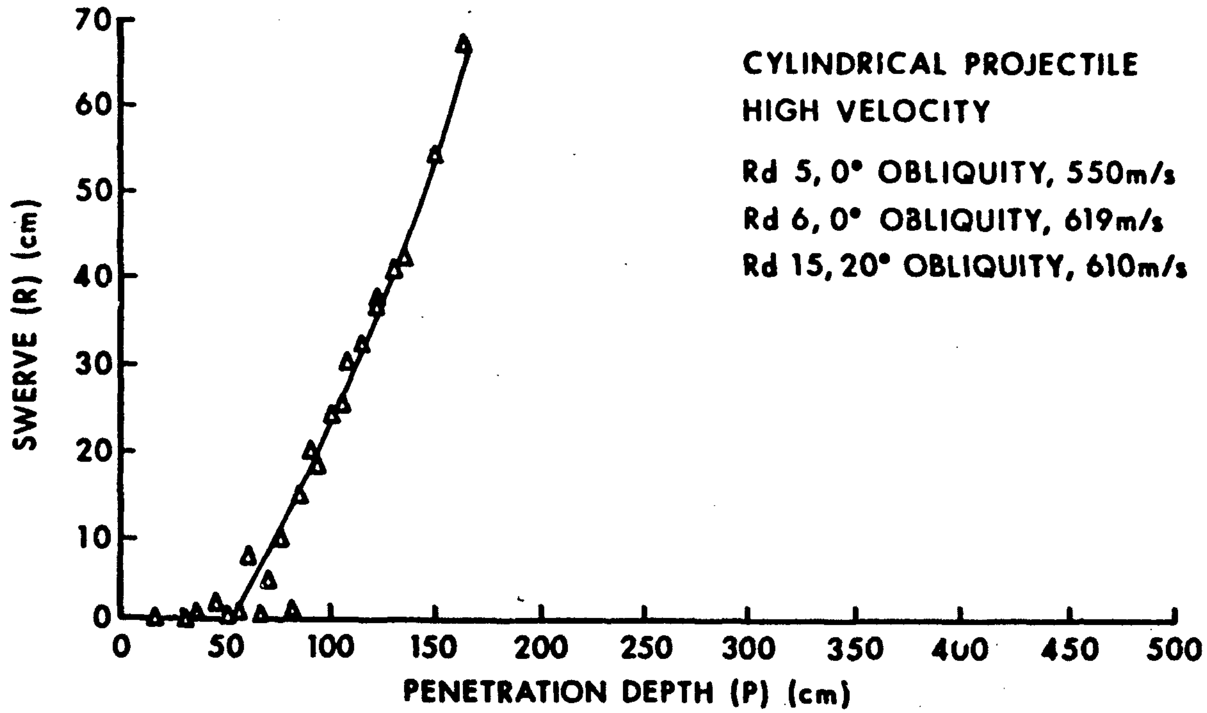

Figure 28. Swerve vs. Penetration Depth, Combined Cylindrical Projectile, High Velocity Rounds

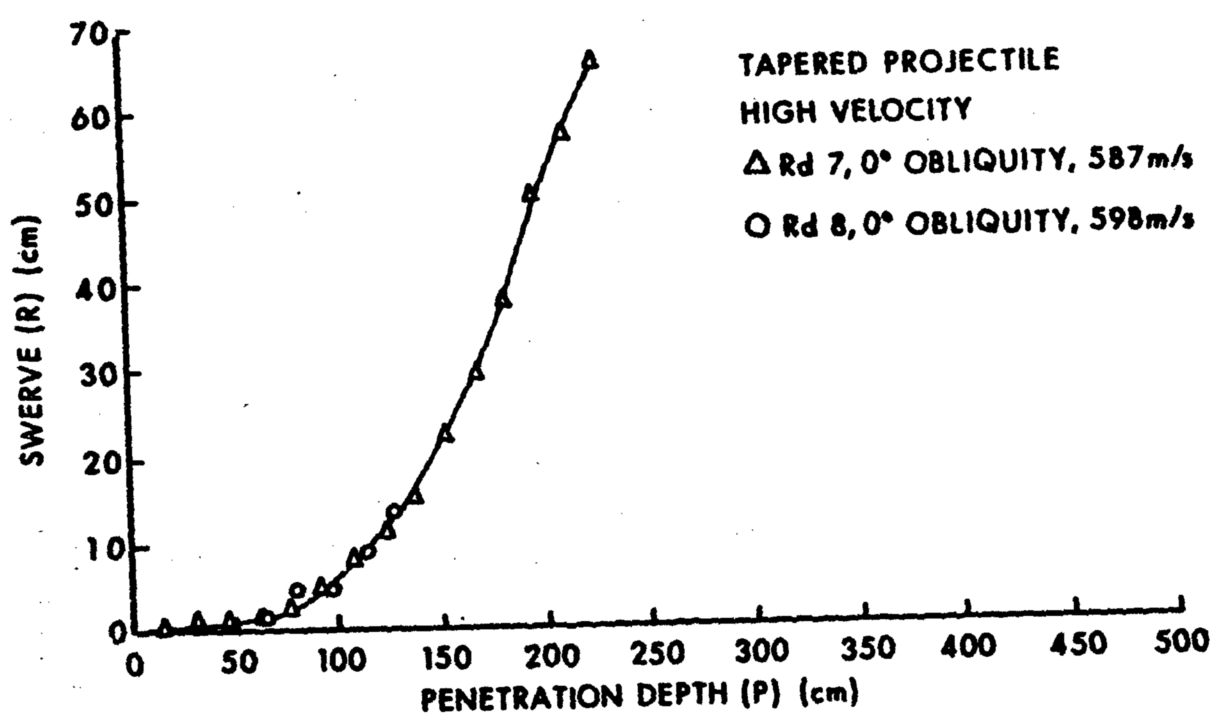

Figure 29. Swerve vs. Penetration Depth, Combined Tapered Projectile, High Velocity Rounds

We are now in a position to compare the relative stabilities of the two projectiles at high and low velocities. Ignoring minor fluctuations, the growth of swerve with effective line of sight distance can be estimated by visualizing a straight line through pooled data in Figures 26 through 29. The slope of the line is then a measure of the relative instability of the projectile, as well as of the deviation from the shot line. The results are:

Projectile	Nominal Striking Velocity (m/s)	Deviation Angle (deg)
Tapered	300	5
Cylindrical	300	45
Tapered	600	30
Cylindrical	600	30

The results are striking! At the lower velocity the cylindrical projectile's instability is an order of magnitude greater than the tapered. Further Figure 27 shows distinct fluctuations about the mean swerve. This is a manifestation of stabilizing forces at work. We conclude that contact between the clay and the aft portion of the projectile was made.

At the higher velocity both the tapered and the cylindrical projectiles have about the same degree of instability, about 2/3 that of the cylindrical projectile at the lower velocity. It would seem that the taper angle was insufficient to achieve contact between the clay and the aft section of the projectile at the higher velocity. This means, then, that the taper angle required for reducing instability must be increased for increasing striking velocity even though the level of instability reduces therewith.

VIII. CONCLUSIONS

Low L/D projectiles with tapered bodies appear to be a feasible solution for systems requiring predictable deep earth penetrators.

Obliquity up to 20 degrees poses no problem.

Minimum body taper required for stability probably increases with increasing striking velocity.

For such velocities and shapes where contact between clay and the aft end of the projectile has not taken place (such as the cylindrical shape base), path deviation decreases with increasing striking velocity.

Delay of onset of rapid yaw and swerve growth is increased as striking yaw is decreased, markedly so for very small yaws.

Absence of the five centimetre concrete face on the clay target would not likely alter the above conclusions.

IX. RECOMMENDATIONS

The authors strongly recommend that the tapered projectile concept be explored further as an earth penetrator both for tactical nuclear and conventional weapon systems. We further recommend that this exploration be done in model scale by using flash radiography, 300 kev sources, in order that swerve, yaw, time, and distance be all tied together and in order to observe visually the contact between the earth and projectile.

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